

# New Technologies and Climate Change

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## Abstract.

Climate change, expected to cause increasingly severe problems over the coming decades and centuries, can be controlled by applying new technologies that can also be developed over the coming decades. To do this, we must first define the fundamental physics of the problem. Second, we must define the new technologies required to solve the problem. Third, we must develop the new technologies. A central issue is the control of global atmospheric composition, and, in particular, the removal of excess atmospheric CO<sub>2</sub>. We review the energetic requirements of filtering and compressing CO<sub>2</sub> on a planetary scale, and then outline how one new technology, molecular manufacturing, could accomplish this task.

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## Introduction

A large fraction of anthropogenic climate change resulting from CO<sub>2</sub> emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO<sub>2</sub> from the atmosphere over a sustained period.

The IPCC (Intergovernmental Panel on Climate Change), 2013<sup>1</sup>

There is widespread concern that anthropogenic changes in the composition of the earth's atmosphere could, if uncorrected, have widespread adverse environmental consequences and negative impacts on human well-being.

While several greenhouse gases have been highlighted, atmospheric carbon dioxide levels in particular have increased from pre-industrial levels of ~280 ppm (**p**arts **p**er **m**illion) to current levels of ~400 ppm, with significant further increases expected. We refer to the additional 120 ppm of CO<sub>2</sub> in the atmosphere as “excess atmospheric CO<sub>2</sub>”.<sup>2</sup> Total production of CO<sub>2</sub> in 2013 was 35.3 billion tonnes, or 3.8% of the excess atmospheric CO<sub>2</sub>.<sup>3</sup> International collective action is not always viewed as a reliable method of reducing global annual production of CO<sub>2</sub>.

Development of a technology capable of removing the excess atmospheric CO<sub>2</sub> would, therefore, be generally viewed as desirable as it would provide an option for relatively rapidly restoring atmospheric CO<sub>2</sub> to pre-industrial levels. Such a technology has been more colloquially referred to as a “super carbon sucking machine”.<sup>4</sup>

## Fundamental Physics

To remove the excess atmospheric CO<sub>2</sub> from the atmosphere, we must separate out a certain amount of gas (the excess CO<sub>2</sub> being removed), and then sequester it, under pressure, in a containment system, possibly consisting of some number of containers.

The processes of sequestration and compression will require energy. We must determine how much energy and the rate of energy usage (power). While energy is measured in joules, and power is measured in joules per second or watts, these units do not convey an intuitive feel for the magnitudes

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<sup>1</sup> Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis Summary for Policymakers; 27 September 2013.

<sup>2</sup> This terminology is used as a convenience and should not be taken as an endorsement of any particular level of atmospheric CO<sub>2</sub>. Determining a desirable planetary level of CO<sub>2</sub> is beyond the scope of this paper.

<sup>3</sup> *Trends in Global CO<sub>2</sub> Emissions, 2014 Report*. [http://edgar.jrc.ec.europa.eu/news\\_docs/jrc-2014-trends-in-global-co2-emissions-2014-report-93171.pdf](http://edgar.jrc.ec.europa.eu/news_docs/jrc-2014-trends-in-global-co2-emissions-2014-report-93171.pdf). One tonne is 1,000 kg. The 2013 annual production of CO<sub>2</sub> can also be expressed as  $4.8 \times 10^{38}$  molecules of CO<sub>2</sub>. As total world energy usage for 2013 was  $5.7 \times 10^{20}$  J, we are getting 1,200 zJ per CO<sub>2</sub> molecule produced, on average. As a point of comparison, burning methane yields ~1332 zJ per CO<sub>2</sub> molecule produced.

<sup>4</sup> Real Time with Bill Maher, 2015-08-07. <https://youtu.be/nZ2cCPRS-Q8?t=120>. Also *Can Sucking CO<sub>2</sub> Out of the Atmosphere Really Work?* by Eli Kintisch, MIT Technology Review, October 7, 2014, <https://www.technologyreview.com/s/531346/can-sucking-co2-out-of-the-atmosphere-really-work/>.

we are dealing with. If we are to understand energy usage on a planetary scale, we must talk about energy and power in ways that are intuitive and understandable.

## Power and Energy

A vast amount of energy reaches the earth from the sun, energy which we could, at least in principle and increasingly in practice, devote to solving the problems facing humanity. What is the total solar power reaching the entire earth? To determine this, we need to know two things: (a) the “solar constant”: the energy carried by the sunlight reaching each square meter of space in the vicinity of the earth each second, and (b) the cross sectional area of the earth facing the sun. From geometry, we know the latter is the total surface area of the earth divided by 4.

The solar constant is about  $1,367 \text{ W/m}^2$ . The surface area of the earth is  $5.1 \times 10^{14} \text{ m}^2$ . Multiplying and dividing by 4 gives  $1.74 \times 10^{17} \text{ W}$ , the total power reaching the earth from sunlight.<sup>5</sup>

This is our version of the solar constant. We’ll call it the Whole Earth Solar Constant, or WESC.<sup>6</sup> The Whole Earth Solar Constant can be used as a unit of power convenient for dealing with global problems, a unit of power that, by definition, is exactly equal to  $1.74 \times 10^{17} \text{ W}$ .

The Whole Earth Solar Constant can be used to define units of energy by multiplying it by units of time. That is, if we multiply the Whole Earth Solar Constant by one year, we get  $\sim 5.5 \times 10^{24} \text{ J}$ , a unit of energy. We could call this a “solar year of energy” or, where the context was clear, the shorter “solar year”.<sup>7</sup> We could also multiply the Whole Earth Solar Constant by one day to get one solar day.<sup>8</sup> Similarly, we can have “solar hours”, “solar weeks”, and “solar months”.

That is, we can talk about a solar second ( $1.74 \times 10^{17} \text{ J}$ ), a solar minute ( $\sim 1.04 \times 10^{19} \text{ J}$ ), a solar hour ( $\sim 6.3 \times 10^{20} \text{ J}$ ), a solar day ( $\sim 1.5 \times 10^{22} \text{ J}$ ), a solar month ( $\sim 4.6 \times 10^{23} \text{ J}$ ), a solar year ( $\sim 5.5 \times 10^{24} \text{ J}$ ), a solar decade ( $\sim 5.5 \times 10^{25} \text{ J}$ ) or a solar century ( $\sim 5.5 \times 10^{26} \text{ J}$ ).

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<sup>5</sup> As the power output of the sun varies, the solar “constant” also varies, reducing the need for great precision in computations involving this constant. For more information see [https://en.wikipedia.org/wiki/Solar\\_constant](https://en.wikipedia.org/wiki/Solar_constant). Watts express power as joules per second, or J/s.

<sup>6</sup> Note that the Whole Earth Solar Constant is a well-defined exact value that has two useful properties. First, its magnitude is convenient for thinking about problems that involve the Earth’s climate, and second, by definition it is an exact value. While the actual amount of power reaching the earth from the sun might differ to some degree from the WESC, the WESC itself is exact. Its purpose is not to be a precise measure of the power reaching the earth from the sun, but to be an exact unit that is approximately equal to the power reaching the earth from the sun, and hence to provide a useful unit of energy when thinking about problems on a planetary scale.

<sup>7</sup> This would have to be distinguished from a “solar year” representing a unit of time, a common usage in many other contexts.

<sup>8</sup> One solar day can also be expressed in joules. In this case, it would be  $1.74 \times 10^{17} \text{ W} \times 24 \times 60 \times 60 \text{ seconds}$ , giving us  $\sim 1.5 \times 10^{22} \text{ J}$ .

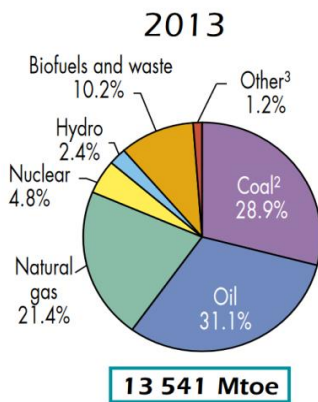
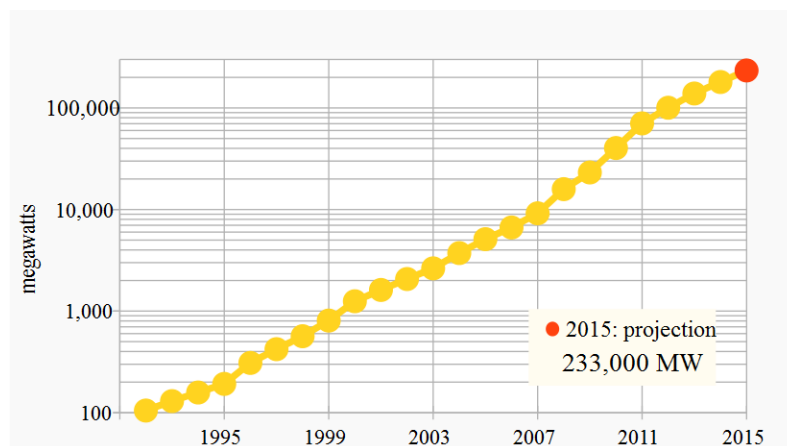


Figure 1. Total World Energy Usage for the year 2013:  $5.7 \times 10^{20}$  J.

To provide a sense of scale the estimated 2013 total world energy usage was just  $5.7 \times 10^{20}$  J (see Figure 1, left).<sup>9</sup> By comparison, one solar hour is  $6.3 \times 10^{20}$  J. That is, the energy reaching the earth from the sun in just one hour is enough to power our entire human civilization for a year. One solar year is almost 10,000 times larger than the total annual human energy usage.

It is worth restating this: the power that humans generate and use, combining coal, oil, natural gas, hydroelectric power, nuclear power, and everything else, is about 10,000 times smaller than the total power the earth receives from the sunlight shining on our planet. On a planetary scale, today's human power usage is almost insignificant.

Our use of solar power is increasing exponentially.<sup>10</sup>



**Global cumulative PhotoVoltaic (PV) capacity in MW since 1992**

[https://upload.wikimedia.org/wikipedia/commons/7/77/PV\\_cume\\_semi\\_log\\_chart\\_2014\\_estimate.svg](https://upload.wikimedia.org/wikipedia/commons/7/77/PV_cume_semi_log_chart_2014_estimate.svg)

Solar power usage in 1995 was almost 200MW, while 20 years later in 2015 it was just over 3 orders of magnitude greater at 233,000 MW. That's a factor of just over 1,000 in 20 years, or a doubling time of only slightly less than 2 years. If such progress continues for the next 20 years (and there is every reason to believe this kind of technology-driven trend *will* continue), then in 2035 global photovoltaic capacity will be 233,000,000 MW or  $2.33 \times 10^{14}$  W: over 0.1% of the total solar power reaching the earth from the sun,<sup>11</sup> or 13 times total world energy usage for the year 2013. The trend data says total global

<sup>9</sup> 2015 Key World Energy Statistics,

[http://www.iea.org/publications/freepublications/publication/KeyWorld\\_Statistics\\_2015.pdf](http://www.iea.org/publications/freepublications/publication/KeyWorld_Statistics_2015.pdf)

<sup>10</sup> See *Growth of photovoltaics* ([https://en.wikipedia.org/wiki/Growth\\_of\\_photovoltaics](https://en.wikipedia.org/wiki/Growth_of_photovoltaics)).

<sup>11</sup> A point that might be lost in this discussion is that the global photovoltaic capacity is generated from incident sunlight that might have as much as ten times the actual raw power, as conversion inefficiencies will result in less electrical power generated than the actual power in the sunlight entering the photocollector. This difference becomes significant in discussions of the total footprint of the photovoltaic collectors, and of the limits to global photovoltaic capacity when the total surface area of the earth that can be devoted to the collection of solar power becomes an issue. We sidestep these issues in the present discussion by limiting total power consumption to values well below 0.1% of the total incident sunlight reaching the earth.

photovoltaic capacity will still be doubling every 2 years in 2035, and fundamental physics says there will still be ample opportunity for continued growth. Technology trends like this continue until they either reach some fundamental physical or economic limit, or until the technology is rendered irrelevant by something better.

If progress like this seems unbelievable, consider that in 1800 it took 6 weeks to travel from New York to Chicago,<sup>12</sup> while today, it takes under 3 hours by air. In 1956 an IBM 650 CPU weighed 1,966 lbs, a system typically had 2,000 words of memory, a 12.96 millisecond multiply time, and cost \$150,000.<sup>13</sup> Today, 60 years later, for one hundredth the price, you can buy a system with 32GB of RAM, a 3TB disk drive, and a quad core 4GHz processor that weighs 27 pounds.<sup>14</sup>

Today, tapping into a significant fraction of the solar power streaming down from the sun onto the earth seems far away. According to decades of technology trend data, by 2035 we'll be doing just that, and the fraction will still be growing.

If we have multi-decadal concerns, technology trends are a reality that we must take into account if we are to make accurate forecasts. We will have, by today's standards, immense amounts of energy at our disposal. To think otherwise is to ignore solid trend data from decades of technology development, as well as the basic physics of solar power. To talk about the climate in 2100 without properly assessing the impact of exponentially advancing technologies is to make a grave error in forecasting.

## Avogadro's Number and the Atmospheric Number

Besides measuring the power and energy we will need, we will have to measure the size of the atmosphere. We have the usual problem of whether we want to measure the atmosphere by counting molecules (which would be similar to using moles of a substance, where one mole is Avogadro's number of molecules of the substance) or by measuring its mass. We choose to measure the atmosphere by counting molecules, and therefore we need to compute the total number of molecules in the atmosphere. We will call this number the Atmospheric number.

In some sense, we are simply substituting the Atmospheric number for the more familiar Avogadro's number, making calculations of atmospheric composition more intuitive.

Just as one mole of a substance is Avogadro's number of particles of that substance, so one Atmosphere of a substance is one Atmospheric number of a substance, or  $1.06 \times 10^{44}$  molecules of the given

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<sup>12</sup> *Maps of the day: Travel times from NYC in 1800, 1830, 1857 and 1930* <https://www.aei.org/publication/maps-of-the-day-travel-times-from-nyc-in-1800-1830-1857-and-1930/>

<sup>13</sup> <https://www.landley.net/history/mirror/ibm/ibm650.htm>

<sup>14</sup> Dell XPS 8900 Desktop - Intel Core i7-6700 6th Generation Quad-Core Skylake up to 4.0 GHz, 32GB DDR4 Memory, 1TB SSD + 3TB SATA Hard Drive, 4GB Nvidia GeForce GTX 745, Windows 10. \$1,449.00 on Amazon.

substance.<sup>15</sup> Today, the ~400 ppm of CO<sub>2</sub> in the atmosphere are 400/1,000,000 or 0.0004 of an Atmosphere of CO<sub>2</sub>, or  $0.0004 \times 1.06 \times 10^{44} = 4.24 \times 10^{40}$  molecules of CO<sub>2</sub>.

## Volume of Compressed CO<sub>2</sub>

The physics involved in compressing the excess CO<sub>2</sub> in the atmosphere involves both the energy required, and the volumes of the uncompressed and the compressed CO<sub>2</sub>. We start by counting molecules and computing volumes.

Today, we have 400 ppm of CO<sub>2</sub> in the atmosphere. The pre-industrial level was 280 ppm. We've added 120 ppm. This means the number of excess CO<sub>2</sub> gas molecules is 0.000120 (120 ppm as a decimal number) multiplied by the Atmospheric number. This product is  $1.27 \times 10^{40}$  CO<sub>2</sub> molecules.<sup>16</sup>

How big a volume will this much CO<sub>2</sub> occupy, once it's compressed to 100 atmospheres for long term disposal?

In the approximate range of 30 to 100 atmospheres CO<sub>2</sub> is liquid at "ordinary" temperatures, with a density that can vary from 800 to 1200 kg/m<sup>3</sup>. We will approximate this as ~1000 kg/m<sup>3</sup>. One CO<sub>2</sub> molecule weighs 44.01 Atomic Mass Units, with one AMU weighing  $1.660\,539\,040 \times 10^{-27}$  kg.<sup>17</sup> Multiplying gives  $7.308 \times 10^{-26}$  kg per CO<sub>2</sub> molecule. Our  $1.27 \times 10^{40}$  molecules of CO<sub>2</sub> therefore has a mass of ~ $10^{15}$  kg, or a volume of ~ $10^{12}$  m<sup>3</sup>. This can also be thought of as the volume of a cube with edges ~10 km in length.

Restating and summarizing: to restore the atmosphere to pre-industrial levels of CO<sub>2</sub> would require that we store a lake of CO<sub>2</sub> roughly the size of a cube 10 km on each edge, and that the lake be compressed to something like 100 atmospheres.

This volume of liquid CO<sub>2</sub> could be stored in a variety of ways. One possibility would be as lakes of CO<sub>2</sub> on the ocean floor. The pressure at depths greater than 3,200 feet is greater than 100 atmospheres. Storage in deep geological formations has also been proposed. Alternatively, one might choose storage in a large number of small and robust pressure containers, inexpensively manufacturable by

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<sup>15</sup> As before, we take  $1.06 \times 10^{44}$  to be exact, and as definitional, rather than approximating some physical value that could be measured with greater accuracy. This value can be approximately computed from the mass of the atmosphere ( $5.1 \times 10^{18}$  kg) and mean molecular weight (0.02897 kg) as  $1.76 \times 10^{20}$  moles. When multiplied by Avogadro's number,  $6.022140857 \times 10^{23}$ , we get  $\sim 1.06 \times 10^{44}$ .

<sup>16</sup> While removing  $1.27 \times 10^{40}$  CO<sub>2</sub> molecules from the atmosphere would restore CO<sub>2</sub> levels to something approximating their pre-industrial levels, human and natural sources would simultaneously be adding additional CO<sub>2</sub>, while natural sinks would be absorbing it, making calculation of the exact CO<sub>2</sub> level following such a large scale removal a complex undertaking. To provide some feel for the magnitudes involved, total annual production of CO<sub>2</sub> in 2013 was  $4.8 \times 10^{38}$  CO<sub>2</sub> molecules, or 3.8% of the  $1.27 \times 10^{40}$  excess atmospheric CO<sub>2</sub> molecules. A more complete analysis of the sources and sinks of CO<sub>2</sub>, and how removal of excess atmospheric CO<sub>2</sub> would influence them, is beyond the scope of this paper.

<sup>17</sup> *The NIST Reference on Constants, Units and Uncertainty*, <http://physics.nist.gov/cgi-bin/cuu/Value?tukg>

nanofactories. Such containers could range in size from under a micron to many meters, depending on system design issues.

Storage of CO<sub>2</sub>, once compressed, is generally viewed as a solvable problem.<sup>18</sup> The future availability of nanofactories further strengthens this conclusion.<sup>19</sup>

## Energy to Compress CO<sub>2</sub>

Compression of CO<sub>2</sub> to a few tens of atmospheres (at which point it becomes a liquid) requires energy. We now compute an upper bound on the energy required to compress our lake of CO<sub>2</sub> from its original uncompressed gaseous state to its compressed state at 100 atmospheres.

If we assume the temperature is such that CO<sub>2</sub> will liquefy before reaching 100 atmospheres (in a particular system of interest), then we can readily bound the amount of energy required to compress it. If we take the worst case, and assume the initial pressure of CO<sub>2</sub> before compression is  $c_1 = \sim 0.000280$  atmospheres,<sup>20</sup> and the final pressure is  $c_2 = 100$  atmospheres (the pressure once stored) we have the total energy required to pump down the excess CO<sub>2</sub> as  $\sim n k T \ln(c_2/c_1)$  (upper bounding the energy by treating CO<sub>2</sub> as an ideal gas, even though it will actually liquify at some point during the compression process). At  $T = 300\text{K}$  and with Boltzmann's constant  $k = 1.38064852 \times 10^{-23}$ , the energy to compress one molecule of CO<sub>2</sub> into a liquid is  $\sim 53$  zJ. Multiplying by the total number of excess atmospheric CO<sub>2</sub> molecules,  $n = 1.27 \times 10^{40}$ , gives the energy required to compress all of the excess atmospheric CO<sub>2</sub>: less than  $6.73 \times 10^{20}$  J, or little more than one solar hour (recall that one solar hour =  $6.3 \times 10^{20}$  J).

If we absorbed one solar hour of power over ten years of time, the entire process could use 0.001% of the incident sunlight reaching the earth. This is just the ratio of one hour to one decade, taken as a percentage. This is worth repeating: we could remove all of the excess atmospheric CO<sub>2</sub> within a decade, given an appropriate deployment of solar powered molecular machines able to capture and compress it, using only 0.001% of the sunshine reaching the earth. Recall that by 2035, we can reasonably expect, as a civilization, to be generating solar power equivalent to 0.1% of the sunshine reaching the earth.

A more detailed analysis of the total system, including actual power requirements (as opposed to the more idealized power requirements computed here) has been provided by Freitas.<sup>21</sup> In that approach, the solar powered molecular machines are deployed as artificial lily pads that absorb sunshine while station-keeping in isolated regions of the ocean, dropping small (2 cm radius) diamond containers holding compressed CO<sub>2</sub> onto the ocean floor. Because of the need to process a small fraction of the CO<sub>2</sub>

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<sup>18</sup> See, for example, the Carbon Capture and Sequestration Technologies Program at MIT, <https://sequestration.mit.edu/>; or *Carbon Capture and Storage from Fossil Fuel Use* by Howard Herzog and Dan Golomb, [http://sequestration.mit.edu/pdf/encyclopedia\\_of\\_energy\\_article.pdf](http://sequestration.mit.edu/pdf/encyclopedia_of_energy_article.pdf)

<sup>19</sup> Nanofactory Collaboration, <http://www.molecularassembler.com/Nanofactory/>

<sup>20</sup> A crude but effective bound on the actual partial pressure of CO<sub>2</sub>, which changes from 400 ppm to 280 ppm during its removal from the atmosphere.

<sup>21</sup> Robert A. Freitas Jr., "The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture," IMM Report No. 45, December 2015; <http://www.imm.org/Reports/rep045.pdf>



to provide the carbon to make the diamond containers, and because of the inclusion of various energetic conversion inefficiencies, Freitas concluded that the power required to sequester  $50 \times 10^{12}$  kg/yr CO<sub>2</sub> would be  $3.24 \times 10^{12}$  W (3,240,000 MW). He computed that removing  $10^{15}$  kg (the excess atmospheric CO<sub>2</sub>) would take 20 years at this rate and require only  $2 \times 10^{21}$  J or ~3.5 solar hours. This is just 0.002% of the incident sunlight reaching the earth over that 20 year period.

Freitas' estimate of 3.5 solar hours of power to remove the excess atmospheric CO<sub>2</sub>, taking into account various inefficiencies and additional systems costs, is consistent with our more idealized estimate of 1 solar hour based on the assumption of no conversion inefficiencies and no additional system costs.

Viewed from this perspective, it is clear that the energy demands of removing CO<sub>2</sub> from the atmosphere, from a planetary perspective, are almost insignificant. Even allowing for solar conversion inefficiencies and other factors, it's clear that abundant solar power is more than adequate to remove any desired amount of CO<sub>2</sub> from the atmosphere.

## New Technologies: CO<sub>2</sub> Filtration and Molecular Manufacturing

We have defined the fundamental physics of the problem. We can see how much energy is required to compress all of the excess atmospheric CO<sub>2</sub>. We can see where that energy could reasonably be obtained: from solar power. Extrapolation of the exponential growth of solar power shows this source of energy should be sufficient for this application somewhere in the 2030s. We can see where the excess CO<sub>2</sub> would be stored, once sequestered.

In short, it seems as though most of the relevant technologies will be in place sometime in the 2030s.<sup>22</sup> The one remaining issue is the CO<sub>2</sub> filtration technology.

Before focusing on CO<sub>2</sub> filtration in particular, we briefly review previously designed and studied binding sites and atomically precise molecular filters. Some of these are shown below. They illustrate the concepts and provide specific examples.

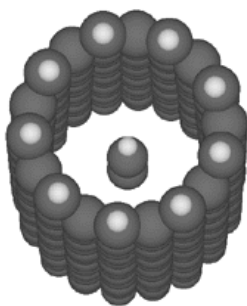
These molecular filters are, at the present time, theoretical. However, as the problem we are dealing with is expected to remain a serious issue for some time, and as current projections indicate the most serious consequences of climate change are projected to occur fifty to one hundred years or more in the future, it seems reasonable to accept a few decades of development time in our planned solution. Technology forecasting is essential if we are to arrive at a realistic assessment of the full range of possible solutions. Limiting ourselves to today's technology to solve tomorrow's problems will necessarily rule out many feasible solutions. As just one example, it is worth considering the fact that we

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<sup>22</sup> The desirability of removing CO<sub>2</sub> directly from the atmosphere, and the general advantages of using future technologies (although usually without mentioning molecular manufacturing in particular), have been commented on by others. See, for example, Lackner et al., *The urgency of the development of CO<sub>2</sub> capture from ambient air*, Proc Natl Acad Sci USA 2012 Aug 14; 109(33): 13156–13162. Published online 2012 Jul 27. doi: 10.1073/pnas.1108765109; PMCID: PMC3421162; by Klaus S. Lackner, Sarah Brennan, Jürg M. Matter, A.-H. Alissa Park, Allen Wright, and Bob van der Zwaana.

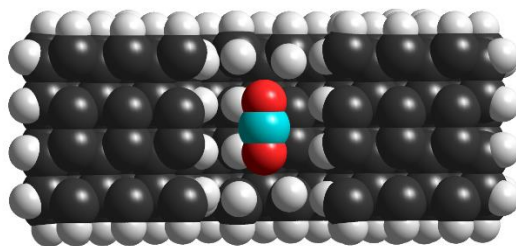
could not feed the over 7 billion people who are alive today had we confined ourselves to using the technology of 100 years ago. Likewise, it is reasonable to assume that new technologies that we develop during the coming decades are likely to play a pivotal role in dealing with the problems that we can also foresee as being potentially significant in that time frame.

It should be possible to build molecular filters by using molecular manufacturing, a technology that, in the words of Richard Feynman, "... cannot be avoided."<sup>23</sup>



A (9,0) nanotube can serve as a simple atomically precise binding site for CO<sub>2</sub> with an affinity of very roughly 125 zJ.

Removal of the CO<sub>2</sub> molecule from the site can be done with a polyyne rod.<sup>24</sup>



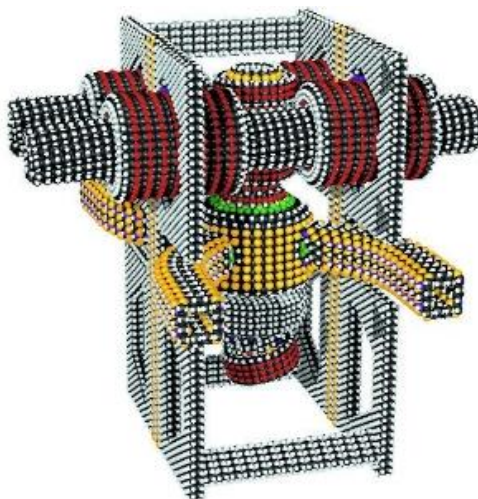
A CO<sub>2</sub> binding site could also be made from hexagonal diamond (side view of section, C in CO<sub>2</sub> is shown in cyan for visibility).

Multi-stage cascade systems can achieve very high purities of the filtered product.

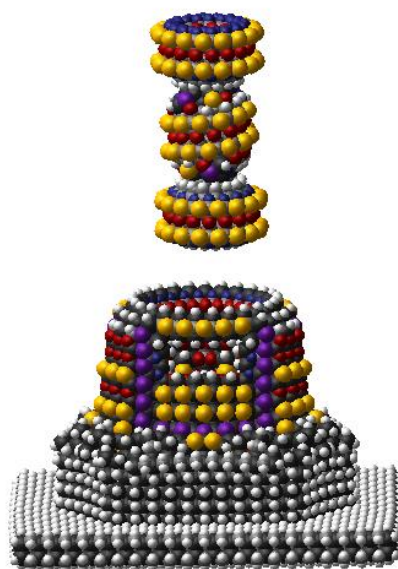
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<sup>23</sup> *There's Plenty of Room at the Bottom*, by Richard P. Feynman, Caltech Engineering and Science, Volume 23:5, February 1960, pp 22-36. <http://www.zyvex.com/nanotech/feynman.html>

<sup>24</sup> *Binding sites for use in a simple assembler*, by Ralph C. Merkle, Nanotechnology **8** (1997) pages 23-28. <http://www.merkle.com/merkleDir/papers.html>. *Nanosystems: Molecular Machinery, Manufacturing and Computation*, by K. Eric Drexler (1992) Wiley. *The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture*, by Robert A. Freitas Jr., IMM Report No. 45, December 2015; <http://www.imm.org/Reports/rep045.pdf>



A molecular filter to separate CH<sub>4</sub> from C<sub>2</sub>H<sub>2</sub> using the “revolver” design<sup>25</sup>.



A neon pump modeled at the Caltech Molecular Simulation Center<sup>26</sup>

## Energy to Filter CO<sub>2</sub>

A conceptually simple method of filtering CO<sub>2</sub> from the atmosphere, and one which allows us to easily understand the energy required for the process, is to use an idealized filter that freely passes CO<sub>2</sub>, does

<sup>25</sup> Nanorex, unpublished.

<sup>26</sup> *Molecular mechanics and molecular dynamics analysis of Drexler–Merkle gears and neon pump*, by T Cagin, A Jaramillo-Botero, G Gao and W A Goddard III, *Nanotechnology* **9** (1998) 143–152.  
<http://www.wag.caltech.edu/home-pages/tahir/PDF/nanotech1.pdf>

not pass anything else, and imposes no energetic cost for its services.<sup>27</sup> This perspective makes it easier to understand what the total energy costs must be by focusing our attention on the energetic costs of compressing the CO<sub>2</sub> that has been filtered from the atmosphere.<sup>28</sup>

That is, we could conceptually place such an idealized CO<sub>2</sub> filter over the intake of the pump which is compressing the CO<sub>2</sub>, and the result would be a compressor that both filtered out the CO<sub>2</sub> from the air and compressed it. After passing through the filter, the CO<sub>2</sub> would be a pure, filtered gas which would have a pressure equal to the partial pressure of CO<sub>2</sub> in the atmosphere. This approximation will remain true provided the rate at which CO<sub>2</sub> is pumped through the filter is slow enough to allow this system (filter and pump) to remain close to equilibrium.

Then we compress the filtered CO<sub>2</sub>. The energetic cost of this compression is the cost of the isothermal compression of the CO<sub>2</sub> from its partial pressure in the atmosphere to its final storage pressure (which, as previously discussed, we assume is 100 atmospheres).

Even if we don't separate out the filtration and compression processes as distinct operations, but instead combine them into a single physical device that carries out both functions simultaneously (as in the proposed atomically precise molecular sortation mechanisms illustrated previously), the conceptual schema outlined above lets us understand and compute the energetic costs involved by simply computing the energetic cost of compression.

That is, the entropic costs of filtration have already been included in the previously calculated energetic costs of compression.<sup>29</sup>

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<sup>27</sup> It is, perhaps, conceptually simpler to think of an atomically precise filter membrane that passes helium freely while blocking all other gases (with the possible exception of molecular hydrogen, H<sub>2</sub>, which we assume is absent from our gas). The feasibility of this is obvious, as it is only necessary to select the pore size in the membrane so small that nothing can fit through it except helium. Thermodynamically, the energy costs of pumping other gases can be analyzed using a similar idealized filter membrane, even if its implementation is more difficult to imagine – or even impossible: an idealized filter membrane that is thermodynamically and entropically correct will yield thermodynamically and entropically correct results even if it cannot be implemented. Note that there is no need to use a passive membrane in an actual implementation. We use an idealized filter membrane simply as a convenience for understanding and a convenience for computing the result. Other methods of filtering CO<sub>2</sub> will require at least the same minimal energy cost even if they use active filter membranes or something completely different.

<sup>28</sup> It is worth explicitly mentioning that this approach deals with entropic energetic costs correctly because the idealized filter membrane complies with standard thermodynamics and statistical mechanics. It is, however, didactically simpler than explicit calculations of entropy.

<sup>29</sup> Those more familiar with the formula used to describe the entropy of two mixed gases, described, for example, by Wikipedia at [https://en.wikipedia.org/wiki/Entropy\\_of\\_mixing](https://en.wikipedia.org/wiki/Entropy_of_mixing), will note that we are not mixing two volumes of gas, both of which are at equal temperature and pressure, but are instead removing CO<sub>2</sub> from one volume (the atmosphere) and compressing the removed gas into a separate much smaller volume at a much higher pressure. The actual size of the second volume is sufficiently small that it can reasonably be neglected for purposes of this calculation, leading to the observation that the energetic cost of compressing the CO<sub>2</sub> from its initial partial pressure in the atmosphere (400 ppm times  $\sim 10^5$  Pa) to its final pressure in the storage system (100 atmospheres or  $\sim 10^7$  Pa) can be used as an upper bound on both the energy used to compress the CO<sub>2</sub> and the entropic cost of isolating the CO<sub>2</sub> from the atmosphere.

While a review and analysis of the feasibility of molecular manufacturing is beyond the scope of this paper, the next section discusses some of the broader policy issues. The interested reader is referred to other sources for a more detailed discussion of the technology.<sup>30</sup>

## Molecular Manufacturing and Policy

The claim being advanced here is that new technologies, specifically including molecular manufacturing, will enable a large net removal of CO<sub>2</sub> from the atmosphere over a period of one to two decades, and that molecular manufacturing could be developed and deployed within a decade or two if an appropriately funded and focused program were pursued.

Broadly speaking either this claim is true, or it is false, and either “society” invests in this new technology or it does not.

	Claim is true	Claim is false
Society invests	Problem solved	Problem not solved
Society doesn't invest	Problem not solved	Problem not solved

There are also the possible solutions that are not based on a large net removal of CO<sub>2</sub> from the atmosphere. These usually center on rapid reductions in the production of CO<sub>2</sub>, with associated debates about their political feasibility. While we have simplified the payoff matrix shown above by assuming that political approaches, largely based on global cooperation, will not produce a satisfactory result, we could extend the payoff matrix into the third dimension to incorporate the “Political solutions work/do not work” aspect into the analysis.

Given societal uncertainty about whether the claim is or is not true, and societal uncertainty about the feasibility and cost of alternative approaches for dealing with climate change, the appropriate response should be a vigorous research effort to develop molecular manufacturing. Feynman gave his famous talk in 1959,<sup>31</sup> Drexler published a detailed technical defense in 1992 (well supported by subsequent research)<sup>32</sup> and numerous other technical articles have been published which provide more than ample support for the feasibility of molecular manufacturing.<sup>33</sup>

The author, having been active as a research scientist in the area of molecular manufacturing since the 1980's, having published many articles, given many talks, filed many patents, and considered the issues in some depth, can state with a high degree of confidence that molecular manufacturing is feasible, could be developed in a one to two decade time frame if a suitably focused and funded program was

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<sup>30</sup> The other references in this paper are a good starting point. The author's web page on nanotechnology, [www.zyvex.com/nano](http://www.zyvex.com/nano), is a second starting point.

<sup>31</sup> There's Plenty of Room at the Bottom, Op. cit.

<sup>32</sup> Nanosystems, Op. cit.

<sup>33</sup> See <http://www.molecularassembler.com/Nanofactory/> and links to articles therein.

adopted, and could solve the problems posed by climate change. Scientists active in molecular manufacturing hold similar opinions.<sup>34</sup>

If political solutions to the anticipated problems that climate change is expected to create should prove unsuccessful, then a solution based on a new technology would be most welcome. Lower cost solutions are always welcome.

As we can reasonably anticipate that any delay in the application of a new technology to remove CO<sub>2</sub> from the atmosphere will result in higher peak CO<sub>2</sub> levels, higher global temperatures, and all the sequelae that follow therefrom, it would seem advisable to develop the new technology as soon as possible. That is, substantial societal investments into the development of molecular manufacturing should begin as soon as possible, with the explicit focus of developing a technology able to effectuate, in the words of the IPCC report, “a large net removal of CO<sub>2</sub> from the atmosphere over a sustained period.”

## Conclusion

The excess atmospheric CO<sub>2</sub> produced by human activity could be filtered and compressed into a volume smaller than a cube with 10 km edges for an energetic cost of only 1 solar hour (the total energy that reaches the earth from the sun in one hour) assuming perfect efficiency of all steps. If we include some reasonable degree of inefficiency for the various steps, when carried out by atomically precise molecular machines manufactured by nanofactories, we still incur an energy cost of no more than a few solar hours. Spread out over a decade or two, this energy cost is much less than 0.01% of the solar energy reaching the earth.

Once our ability to manufacture atomically precise molecular machines has been developed, removing undesired CO<sub>2</sub> (or any other greenhouse gas) from the atmosphere will present no special technical challenges and could be powered by collecting a very modest percentage of the sunlight reaching the earth.

The primary reason for this conclusion is that we’ll be able to shift the burden from current technology and today’s relatively expensive power, to future technology and tomorrow’s inexpensive power. That is, we’ll be able to use molecular machines that use abundant and inexpensive solar power.

Further research and development of molecular manufacturing should be pursued.

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<sup>34</sup> Publications by Freitas and Drexler have already been cited. *The Weather Machine: Nano-enabled Climate Control for the Earth* by J. Storrs Hall, Global Catastrophic Risks 2008 (<https://vimeo.com/2539563>), describes an alternative approach enabled by molecular manufacturing.

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